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Changes in surface soil organic carbon in semiarid degraded Horqin Grassland of northeastern China between the 1980s and the 2010s

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ABSTRACT

Soil organic carbon (SOC) plays an important role in the global carbon cycle and in mitigating climate change. The Horqin Grassland is one of the largest grasslands in China and has undergone serious aeolian desertification in recent decades. We conducted the largest field inventory to date, with the highest density of soil sampling, and explored changes in SOC in the region over the 30-year gap between the 1980s and the 2010s. Our results indicated that the mean SOC density to a depth of 20 cm decreased from 2.58 to 2.21 kg C m^{-2}, while the total SOC storage decreased from 311.11 to 266.70 Tg C, at an average of 12.29 g C m^{-2} yr^{-1}. We ranked the SOC densities by ecosystem as woodland > grassland > cropland > sandy land. The decreased SOC storage in the Horqin Grassland can be ascribed to a combination of increasing temperature, decreasing precipitation, an expansion of the areas of extremely severely desertified land and cropland, and shrinkage of the grassland area. Our results provide an important updated regional baseline for quantifying how SOC storage will respond to future climate change and anthropogenic activities. Our results will also help policy makers determine how to achieve sustainable development of agriculture, forestry, and animal husbandry based on carbon sequestration.

1. Introduction

Soil is the largest reservoir of organic carbon in terrestrial ecosystems, as it holds about three times the amount stored in living vegetation (Lal, 2004a). It is therefore essential to understand changes in soil organic carbon (SOC) as well as its role in the global carbon cycle (Post and Kwon, 2000; Scharlemann et al., 2014). SOC accounts for approximately two-thirds of the carbon involved in active exchanges with the atmosphere in terrestrial ecosystems (Post et al., 1982). The amount of SOC represents the long-term net balance between photosynthesis and total respiration (Schlesinger, 1990). Many studies (Jobbágy and Jackson, 2000; Smith et al., 2008; Muñoz-Rojas et al., 2015; Valtera and Šamonil, 2018; Wang et al., 2018) have documented the link between SOC dynamics and the build-up of atmospheric carbon dioxide (CO_2), and the soil's potential to act as a carbon sink for mitigating climate change.

The SOC pool is highly dynamic, reactive, and sensitive to land use, climate change, and management. Deforestation, degradation of natural ecosystems, and conversion of natural ecosystems into cultivated fields and grazing land have generally decreased SOC (Guo and Gifford, 2002; Smith et al., 2016), whereas afforestation and reforestation, re-establishing grasslands, and implementing conservation tillage can sequester SOC (FAO, 2004; Cantarello et al., 2011; Deng and Shangguan, 2017; Lu et al., 2018). Climate change can significantly affect the SOC level through the ability of changes in temperature, rainfall patterns, and CO_2 concentrations to influence carbon inputs and outputs from soils (Cao and Woodward, 1998; Soleimani et al., 2017).

Lal (2004b) reported that depletion of the global SOC pool, primarily due to land misuse and soil mismanagement, has contributed 78 ± 12 Pg of C to the atmosphere since the industrial revolution, versus global potential SOC sequestration that could reach 0.9 ± 0.3 Pg C yr^{-1} if we adopted restorative land use practices and improved management practices. Kirschbaum (2000) created a model in which a decrease of just 10% in SOC storage would be equivalent to all the anthropogenic CO_2 emitted in the previous 30 years. Bellamy et al. (2005) and Yang et al. (2009) summarized numerous findings from small-scale laboratory incubations, field experiments, and modeling studies that suggested climate warming is likely to be inducing

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carbon loss from soils. However, despite much research, there remains substantial uncertainty about the contribution of SOC dynamics to the historic increase in atmospheric CO_2, and the strategic importance of these dynamics in mitigating future increases in atmospheric CO_2 (Lal, 2004b). In particular, little evidence has been available from large-scale observations based on soil inventory data (Yang et al., 2009).

From 1979 to 1994, China conducted its second National Soil Survey to map and characterize the country's soils (Shi et al., 2004). The soil dataset produced by this survey was regarded as the most detailed and reliable one in China until the present study, and its dataset has been applied widely in soil research. Based on this dataset, SOC storage has been estimated by administrative regions, river watersheds, soil types, and ecosystems at national scale (Wu et al., 2003; Yu et al., 2007a, 2007b); a baseline was created to evaluate changes in SOC storage over several decades for the regional soils of Tibetan grasslands (Yang et al., 2009), for the provincial soils of Jiangsu province (Liao et al., 2009), and for the nation's soils (Wang et al., 2003; Xie et al., 2007; Yang et al., 2010; Zhao et al., 2018).

The Horqin Grassland is one of the largest grasslands in China and almost 80% of this region has undergone aeolian desertification in recent decades (Liu et al., 1996). Therefore, it has become a region of interest for evaluating the effects of desertification control and the carbon sequestration potential of degraded ecosystems through strategies such as afforestation (Zhang et al., 2004; Cao et al., 2008; Li et al., 2013, 2017) and grazing exclusion (Su et al., 2003; Li et al., 2012). However, no research has quantified the long-term SOC changes for the whole region.

The objectives of the present study were to provide an accurate estimate of current SOC storage in the Horqin Grassland, to explore changes in SOC based on a comparison of measurements from 2011 to 2017 (hereafter, "the 2010s") with those in the second National Soil Survey dataset from 1980 to 1987 (hereafter, "the 1980s"), and to establish a baseline for evaluating future changes in SOC storage in the region.

2. Materials and methods

2.1. Study area

The Horqin Grassland (also called the Horqin Sandy Land) is a transition zone between the Inner Mongolian Plateau and China's Northeastern Plains, and is located in the western part of northeastern China (Fig. 1). The present study area covers 13 counties of China's Inner Mongolia Autonomous Region, with a mean elevation of about 430 m above sea level, and an area of about $12.0 \times 10^4\,km^2$ (41°40′38″N to 46°3′25″N, 117°52′12″E to 123°42′48″E). Fig. 2 shows typical current landscapes in this region. The study area is a temperate grassland of the Central Asian Steppe ecosystem, with a continental semiarid monsoon temperate climate regime. The mean annual air temperature is 3 to 7 °C. Mean monthly temperatures range from a minimum of −12.6 to −16.8 °C in January to a maximum of 20.3 to 23.5 °C in July. The mean annual precipitation is 350 to 500 mm, with the highest values in the summer from June to August. Mean annual potential evaporation is 1500 to 2500 mm (Duan et al., 2014).

The zonal soils are classified as Kastanozems and Chernozems based on the Food and Agriculture Organization of the United Nations soil classification system (FAO, 2006), but the current dominant soils are Arenosols as a result of desertification. The native vegetation mainly consists of mesoxerophytes characterized by palatable grass species along with sparsely scattered woody species. However, the area has become dominated by xerophytes and psammophytes as a result of extensive desertification, which has been caused by a combination of climate change and unsustainable land use (Zhao et al., 2003).

2.2. Data acquisition for SOC and bulk density in the 1980s

The soils in 2444 counties, 312 national farms, and 44 forest farms were surveyed during China's second National Soil Survey. In this survey, villages were regarded as the basic sampling unit, yielding a total of 34,411 soil profiles, and the data were then assimilated at larger scales (township, county, city, provincial, and national levels) (Wu et al., 2003; Shi et al., 2004). The 1:1000000 soil maps of China were compiled based on this survey, in which the basic map units were soil families; subsequently, a 1:1000000 Soil Database was generated, which consists of a spatial database, an attribute database, and a reference system (Yu et al., 2007b).

For the present study, we obtained a digital 1:1000000 vector map of SOC concentrations to a depth of 20 cm that derived from the aforementioned soil database and a digital 1:4000000 vector map of soil types for the Horqin Grassland from the Soil Science Data Center, National Earth System Science Data Sharing Infrastructure, National Science & Technology Infrastructure of China (http://soil.geodata.cn/). In our study area, the second National Soil Survey was conducted from 1980 to 1987. We converted the vector map of SOC concentrations into

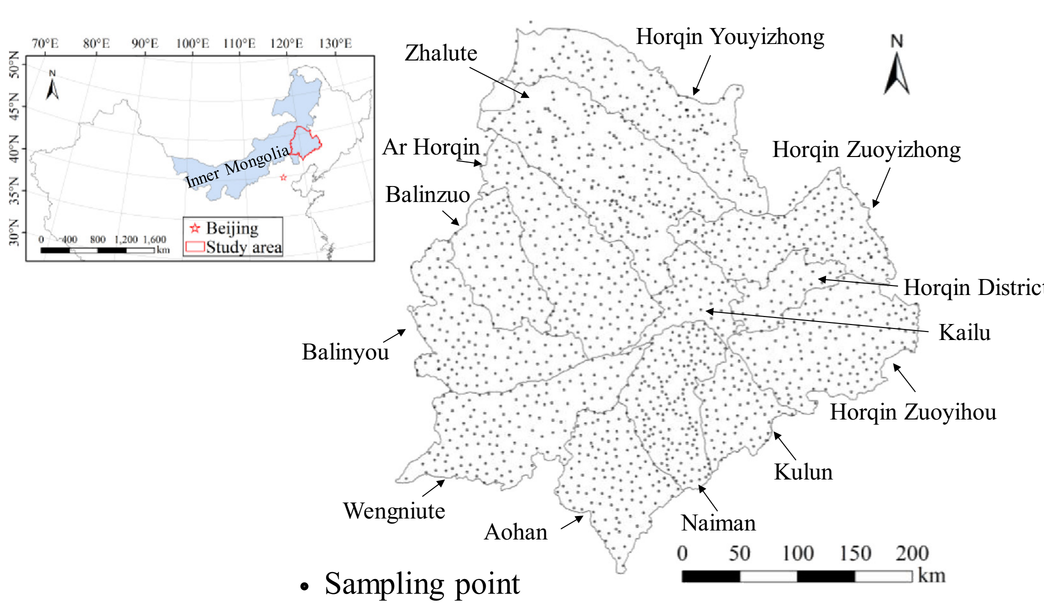

Fig. 1. Locations of the Horqin Grassland and of the soil sampling points (n = 1465). Names are for the 13 counties in the study area.

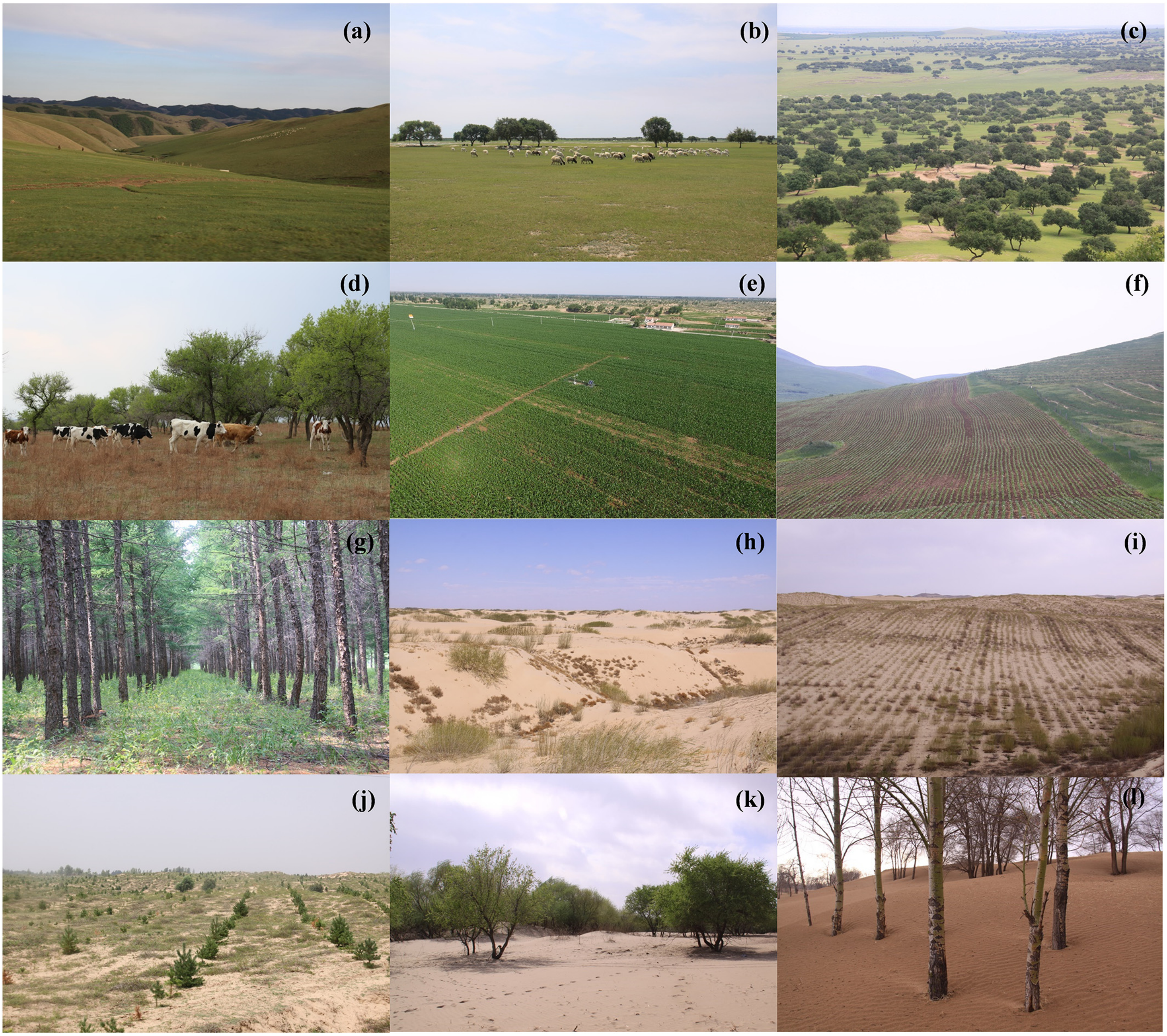

Fig. 2. Photographs of typical land-use and cover types in the Horqin Grassland: (a) mountain grassland interlaced with forest; (b) meadow steppe; (c, d) the dominant native landscape in the past, which was characterized by palatable grass species associated with sparsely scattered woody species (*Acer mono* and *Ulmus pumila*); (e, f) cropland converted, respectively, from meadow steppe and from mountain grassland; (g) tree plantation (*Larix gmelinii*) established in areas with grassland; (h) a typical area of extremely severely desertified land; (i, j) plantations established in areas with extremely severely desertified land using an indigenous leguminous shrub (*Caragana microphylla*) and introduced *Pinus sylvestris* var. *mongolica*, respectively; and (k, l) a woodland soil surface with mobile sands caused by anthropogenic activity such as overgrazing. All images are from the authors' own collection.

a gridded map with a grid size of 1 km × 1 km. This yielded a total of 120,443 cells in the grid for the whole study area.

Because soil bulk density data was not available for the older survey, we developed an empirical relationship [Eq. (1), Fig. 3a] between the SOC concentration and bulk density using actual measured data obtained from 2011 to 2017, and used it to estimate soil bulk density for the 1980s.

$$BD = (-1.363\text{E} - 5)x^3 + 0.001x^2 - 0.040x + 1.554$$
$$(R^2 = 0.573, P < 0.001) \quad (1)$$

where *BD* represents the soil bulk density (in g cm^{-3}) and *x* represents the SOC concentration (in g kg^{-1}). In this analysis, 90% of the data was used to construct the regression equation, which was done using standardized major axis regression, and the remaining 10% was used to validate the relationship. The slope of the relationship between the predicted value and the observed value in the 2010s was not significantly different from 1.0, suggesting that the relationship was valid (Fig. 3b).

2.3. Soil sampling in the 2010s

Soil samples were collected from April to August over a 7-year period from 2011 to 2017. We originally planned to divide the whole study area into 10 km × 10 km cells and collect soil samples from each cell. However, it was not possible to fulfill this plan because of the high spatial heterogeneity of the region and inaccessibility of some parts of the region. In the end, we selected a total of 1465 representative locations, with a mean interval of 6.65 km between sampling sites (Fig. 1). The land-use type, geographical coordinates, and elevation were recorded at each location using a GPS receiver. Soil was sampled

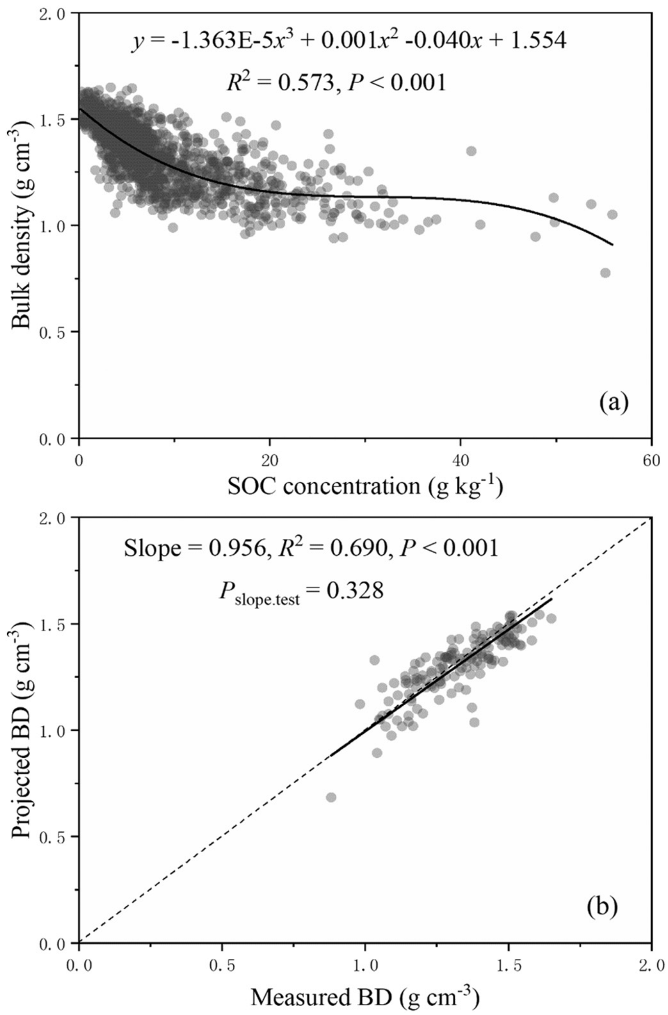

Fig. 3. Relationships (a) between the soil organic carbon (SOC) concentration and bulk density (BD), and (b) between measured and predicted BD in the Horqin Grassland. Data for the SOC concentration and BD were obtained from field measurements at 1465 soil sampling locations from 2011 to 2017. The relationship between SOC and BD in (a) was based on 90% of the data points that were randomly extracted from the dataset; in (b), the remaining 10% of the data points were used to test the reliability of the empirical function; the predicted BD was significantly correlated with measured value, and the slope did not differ significantly from 1. The dashed line in (b) indicates the position at which the estimated BD equals the measured value.

using a soil auger (2.5 cm in diameter) from five layers: 0 to 10, 10 to 20, 20 to 40, 40 to 60, and 60 to 100 cm. To quantify the changes in SOC storage over the 30-year gap since the sampling in the 1980s, however, we only used the data for the combined layer from 0 to 20 cm in the present study, as this depth corresponded to the sampling depth in the 1980s dataset.

One 10 m × 10 m plot was established at each of the 1465 locations. The soil samples were collected randomly at 15 sampling points within each plot and mixed to prepare a single composite sample for each depth layer. Three additional sampling points (replicates) in each plot were selected to determine the soil bulk density, using a soil auger equipped with a stainless-steel cylinder (100 cm^3 in volume) to sample intact soil cores. We calculated the bulk density separately for each of the three samples, then averaged those values to create a single mean value for the sampling location.

In the laboratory, the soil samples were air-dried and hand-sieved through a 2-mm mesh to remove roots and other coarse debris. The stones were manually separated (left on the 2-mm sieve) and weighed, and then the mass-based content was converted to a volumetric equivalent based on the method of Cools and De Vos (2010). We homogenized the fraction < 2 mm in diameter from each sample, then obtained a 60-g subsample using the coning and quartering method. That is, we poured the sample onto a flat surface to create a cone, which we then flattened to produce a disk. We divided the disk into four equal quarters and discarded two quarters on opposite sides of the disk. We repeated the process until the remaining soil represented an appropriate sample size for analysis. The remaining sample was ground to pass through a 0.25-mm mesh before determination of the SOC concentration. Samples of intact soil cores were oven-dried at 105 °C to constant mass to determine their bulk density. We used the Walkley-Black dichromate oxidation procedure (Nelson and Sommers, 1982) to determine the SOC concentration. We chose this method because it was the same method used to analyze the 1980s samples, thereby avoiding any issues that might arise from the use of different methodology.

2.4. Data acquisition for factors that influenced SOC

To understand the mechanisms by which SOC changed during the study period, we created a gridded dataset for the study area that included annual precipitation and mean annual air temperatures between 1980 and 2015, and the land-use types in 1980 and 2015. We tested for significant trends in precipitation and temperature using the Mann-Kendall test and calculated rates of change in precipitation and temperature using linear least-squares regression. We also obtained the values of the normalized-difference vegetation index (NDVI) in 2015 for each sampling location in the dataset from the 2010s. All of these data were provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn/).

2.5. Estimation of SOC density and storage

For the dataset from the 2010s, we first calculated the SOC density (*SOCD*, in kg C m^{-2}) to a depth of 20 cm for each location using Eq. (2)

$$SOCD = SOC \times BD \times T \times (1 - [\theta/100]) \times 0.01 \quad (2)$$

where *SOC* represents the SOC concentration (in g kg^{-1}), *BD* represents the soil bulk density (in g cm^{-3}), *T* represents the thickness of the soil layer (in cm), θ represents the volumetric percentage of stone (> 2 mm) in the soil, and 0.01 represents a unit conversion factor.

We then produced a gridded map of *SOCD* with a 1 km × 1 km grid using version 10.3 of the ArcGIS software (www.esri.com); we applied ordinary kriging to interpolate between data points. We calculated the *SOCD* in the 1980s and the difference between that value and the value in the 2010s, as well as the spatial distribution of the differences and trends over time, using the Raster Calculator tool of ArcGIS. We calculated *SOCD* and storage based on the aggregated data for each county, each soil type, and each land-use type using the Zonal Statistics as Table tool of ArcGIS. We compared actual measurements in the 2010s with corresponding values extracted from the spatial interpolation in the 1980s, and then performed paired-sample *t*-tests to determine whether *SOCD* differed significantly between the two periods (Yang et al., 2010).

Correlations between parameters were calculated using Pearson's correlation coefficient (*r*). Statistical and regression analyses were performed using version 20.0 of the SPSS software (https://www.ibm.com/analytics) and the R Programming Language.

3. Results

3.1. Current spatial patterns of SOCD related to land-use and soil types

Fig. 4 shows the spatial patterns of the land-use and soil types as well as the corresponding *SOCD* for the 2010s. The areas of grassland, cropland, woodland, and sandy land accounted for 38.5, 28.8, 16.2, and

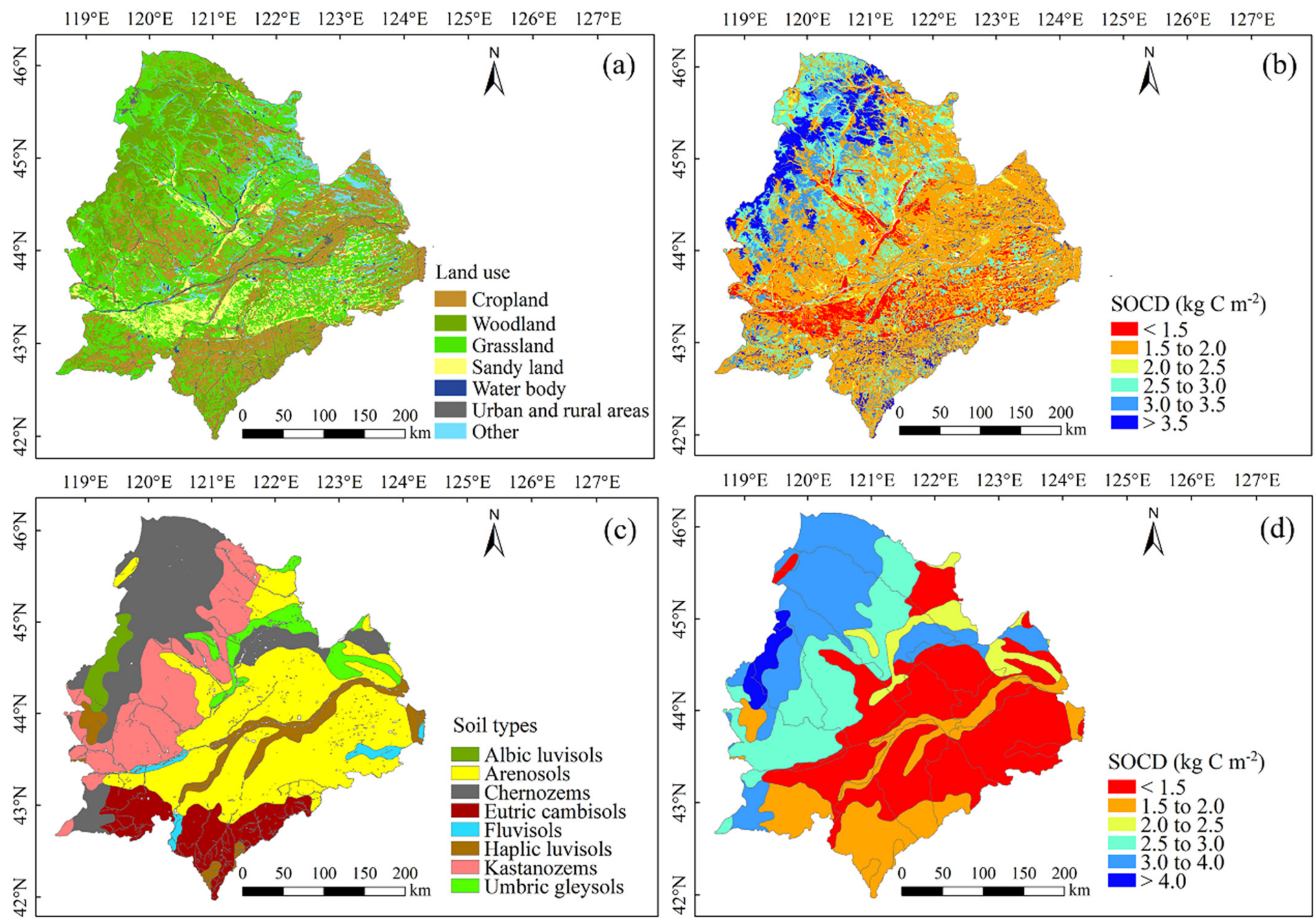

Fig. 4. Spatial patterns of (a) the land use in 2015, (b) the soil organic carbon density (*SOCD*) for the different land-use types in the 2010s, (c) the soil types, and (d) the *SOCD* for the different soil types in the 2010s.

8.0%, respectively, of the total area of Horqin Grassland (Fig. 4a). *SOCD* (kg C m^{-2}) for these four land-use types decreased in the order of woodland (3.31) > grassland (2.24) > cropland (1.97) > sandy land (1.09) (Fig. 4b).

Soil types in the study area were dominated by Arenosols, Chernozems, and Kastanozems, which accounted for 37.0, 21.0, and 17.8%, respectively, of the total area of Horqin Grassland. The soil types that covered the smallest areas were Albic Luvisols and Fluvisols, which accounted for 2.2 and 1.5% of the total area, respectively (Fig. 4c). *SOCD* (kg C m^{-2}) for the eight soil types decreased in the order of Albic luvisols (4.39) > Chernozems (3.81) > Kastanozems (2.57) > Umbric gleysols (2.16) > Eutric cambisols (1.63) > Haplic luvisols (1.62) > Fluvisols (1.33) > Arenosols (1.32) (Fig. 4d).

3.2. Changes in SOC density and storage between the two periods

SOCD for each county (Table 1) in the 1980s ranged from 1.38 to 3.82 kg C m^{-2}, with a mean value of 2.58 kg C m^{-2} for the whole study area, versus a range from 0.86 to 3.64 kg C m^{-2} and a mean value of 2.21 kg C m^{-2} in the 2010s. *SOCD* values in the 2010s were significantly (n = 1465, t = 9.161, P < 0.001) lower than the SOCD values in the 1980s for the study area as a whole. SOC storage in the top 20 cm (Table 1) totaled 311.11 Tg C in the 1980s and 266.70 Tg C in the 2010s, representing a decrease of 44.41 Tg C. This amounted to an average (linear) decrease of 12.29 g C m^{-2} yr^{-1} over the 30-year study period.

SOCD decreased between the 1980s and the 2010s for all land-use types (Table 2). SOC storage showed a great decrease (60.47 Tg C) in grassland and a slight decrease (2.40 Tg C) in sandy land. However, even though the *SOCD* of cropland and woodland decreased by 0.42 and 0.59 kg C m^{-2}, respectively, the corresponding SOC storage increased by 4.36 and 14.72 Tg C. This can be ascribed to the large increase in their areas, which increased by 30.0% for cropland and 53.6% for woodland as a result of (respectively) increased agricultural exploitation and large-scale government afforestation programs (Table 2).

SOCD showed high spatial heterogeneity in both periods (Fig. 5a, b). The lowest SOC densities during both periods were located in the south-central part of the study area, which was dominated by desertified land. The highest SOC densities during both periods were located in the northern part of the study area, which was dominated by mountain woodland and grassland. At the county level, Horqin Zuoyihou and Naiman counties had the lowest mean *SOCD* in the 1980s and the 2010s, respectively, whereas Zhalute County had the highest *SOCD* in both periods (Table 1). The former two counties are located in the southern part of the study area, whereas the latter one is located in the northern part (Fig. 1). The changes in *SOCD* between the two periods also showed high spatial heterogeneity (Fig. 5c). In total, 35.3% of the pixels showed an increase in *SOCD* during the study period, and the remaining 64.7% showed decreased *SOCD* (Fig. 5d).

4. Discussion

We found a net SOC loss of 44.41 Tg C in the surface soil to a depth of 20 cm in the Horqin Grassland between the 1980s and the 2010s (a 30-year period), which represented an average (linear) decrease of 12.29 g C m^{-2} yr^{-1}, if we assumed a constant decrease during the study

Table 1
Changes in the soil organic carbon (SOC) storage and density (*SOCD*) to a depth of 20 cm for each county and for the whole study area from the 1980s to the 2010s. *SOCD* values represent means ± standard deviations (SD).

County	Area (km^2)	1980s		2010s		Change in SOC (2010s minus 1980s)		
		SOCD ($kg\,C\,m^{-2}$)	SOC storage (Tg C)	*SOCD* ($kg\,C\,m^{-2}$)	SOC storage (Tg C)	Density ($kg\,C\,m^{-2}$)	Storage (Tg C)	Rate ($g\,C\,m^{-2}\,yr^{-1}$)
Naiman ($n = 159$)	8184	1.76 ± 0.83	14.40	0.86 ± 0.39	7.04	−0.90	−7.36	−29.98
Kailu ($n = 50$)	4228	2.31 ± 0.64	9.77	1.42 ± 0.32	6.00	−0.89	−3.77	−29.72
Balinyou ($n = 112$)	9829	2.93 ± 1.55	28.80	2.21 ± 1.08	21.72	−0.72	−7.08	−24.01
Kulun ($n = 64$)	4646	1.61 ± 0.63	7.48	1.02 ± 0.33	4.74	−0.59	−2.74	−19.66
Balinzuo ($n = 65$)	6460	3.78 ± 1.56	24.42	3.27 ± 1.09	21.12	−0.51	−3.30	−17.03
Aohan ($n = 120$)	8288	2.13 ± 0.97	17.65	1.66 ± 0.34	13.76	−0.47	−3.89	−15.65
Wengniute ($n = 126$)	11,861	1.82 ± 1.40	21.59	1.39 ± 0.74	16.49	−0.43	−5.10	−14.33
Horqin Zuoyizhong ($n = 142$)	9576	2.05 ± 0.88	19.63	1.68 ± 0.31	16.09	−0.37	−3.54	−12.32
Ar Horqin ($n = 143$)	12,762	2.95 ± 1.49	37.65	2.67 ± 1.07	34.07	−0.28	−3.58	−9.35
Horqin Zuoyihou ($n = 136$)	11,590	1.38 ± 0.83	15.99	1.16 ± 0.27	13.44	−0.22	−2.55	−7.33
Horqin District ($n = 35$)	3497	2.07 ± 0.63	7.24	1.89 ± 0.34	6.61	−0.18	−0.63	−6.01
Zhalute ($n = 188$)	17,205	3.82 ± 1.71	65.72	3.64 ± 1.36	62.63	−0.18	−3.10	−6.00
Horqin Youyizhong ($n = 125$)	12,317	3.31 ± 1.87	40.77	3.49 ± 1.43	42.99	+0.18	+2.22	+6.01
Total study area ($n = 1465$)	120,443	2.58[a]	311.11	2.21[a]	266.70	−0.37	−44.41	−12.29

[a] The average area-weighted total *SOCD*.

period (Table 1). This is a greater decrease than the value for China's Tibetan Plateau that was estimated using a combination of field observations, remote sensing, and modeling. SOC storage in alpine grasslands of the Tibetan Plateau decreased slightly, at a rate of $0.60\,g\,C\,m^{-2}\,yr^{-1}$, from the 1980s to 2004 (Yang et al., 2009), but increased at a rate of $4.66\,g\,C\,m^{-2}\,yr^{-1}$ from 2002 to 2011 (Chen et al., 2017). Both studies sampled the soil to a depth of 30 cm. By contrast, the total provincial topsoil (0 to 20 cm) SOC storage in China's Jiangsu Province increased at a rate of $16.00\,g\,C\,m^{-2}\,yr^{-1}$ from 1982 to 2004, and this result was based on a method similar to the one in the present study (Liao et al., 2009).

For China as a whole, Zhao et al. (2018) reported that croplands showed a net increase of $14.00\,g\,C\,m^{-2}\,yr^{-1}$ in SOC storage to a depth of 20 cm based on the soil sampling locations recorded by the second National Soil Survey of China in the 1980s and soil samples collected in 2011. Xie et al. (2007) found the opposite trend for all of China's grassland, in which SOC storage declined by $63.98\,g\,C\,m^{-2}\,yr^{-1}$ (for a net loss of 3.564 Pg C in an area of 278.51×10^6 ha), based on data from China's second National Soil Survey plus a literature review for the 20-year period from the 1980s to the 2000s. The loss was slower for all of China's soils combined, at an average of $16.42\,g\,C\,m^{-2}\,yr^{-1}$ (for a net loss of 2.860 Pg in an area of 970.94×10^6 ha). The average soil sampling depth was 103.2 and 99.6 cm, respectively. However, the SOC dynamics in China's grassland ecosystems remain controversial. Piao et al. (2009) reported that China's grassland soils acted as a significant C sink from 1982 to 1999, with an increase of $1.81\,g\,C\,m^{-2}\,yr^{-1}$, using a combination of satellite remote sensing with field inventory data estimation. Yang et al. (2010) reported that SOC storage in the upper 30 cm of China's grasslands did not change significantly in the two-decade period between field soil surveys conducted from 2001 to 2005 and data derived from the Second National Soil Survey. Fang et al. (2010) summarized the research conducted from the 1980s to the 2010s and found that SOC storage in China's grasslands did not show a significant change. The discrepancies among these studies can be attributed to the different approaches. In addition, the high heterogeneity among the sampling locations that we observed in the present study suggests that sampling at different locations would produce somewhat different results even if exactly the same method was used. Therefore, long-term direct measurements by repeated soil inventories at regional and national scales are needed to evaluate these estimates.

Climate change and anthropogenic activities are the major factors that affect changes in SOC storage (Trumbore, 1997). Increasing temperature would lead to a net loss of SOC by stimulating decomposition rates, but the loss could be offset by increasing SOC as a result of increases in net primary productivity due to increasing atmospheric CO_2 levels (Kirschbaum, 2000; Davidson and Janssens, 2006). The existence of this tradeoff was supported by the study of Yang et al. (2009) in the Tibetan grasslands. They found that increased rates of decomposition as soils warmed during their two-decade study period may have been compensated for by increased inputs of soil carbon caused by the increased grassland productivity. By contrast, Chen et al. (2017) found that mean annual precipitation was the most important factor driving SOC dynamics across the alpine steppes in their study.

Land-use and cover type change is a key consequence of human activities, and these changes have contributed significantly to the global increase in atmosphere CO_2 since pre-industrial times (IPCC, 2007). The findings in two meta-analyses at a global scale (Guo and Gifford, 2002; Don et al., 2015) indicated that the conversion of natural

Table 2
Changes in the soil organic carbon (SOC) storage and density (*SOCD*) to a depth of 20 cm for the major land-use types from the 1980s to the 2010s. *SOCD* values represent means ± standard deviations (SD).

Land-use type	1980s			2010s			Changes (2010s minus 1980s)		
	Area (km^2)	*SOCD* ($kg\,C\,m^{-2}$)	SOC storage (Tg C)	Area (km^2)	*SOCD* ($kg\,C\,m^{-2}$)	SOC storage (Tg C)	Area (%)	*SOCD* ($kg\,C\,m^{-2}$)	SOC storage (Tg C)
Grassland ($n = 558$)	61,037	2.66 ± 1.55	162.38	45,492	2.24 ± 1.26	101.91	−25.47	−0.42	−60.47
Cropland ($n = 522$)	26,132	2.39 ± 1.19	62.42	33,959	1.97 ± 0.93	66.78	+29.95	−0.42	+4.36
Woodland ($n = 123$)	12,412	3.90 ± 1.82	48.35	19,070	3.31 ± 1.42	63.07	+53.64	−0.59	+14.72
Sandy land[a] ($n = 82$)	8613	1.47 ± 0.85	12.64	9387	1.09 ± 0.73	10.24	+8.99	−0.38	−2.40

[a] Sandy land included only extremely severely desertified land, with a vegetation cover < 5% and a soil surface covered by coarse sand.

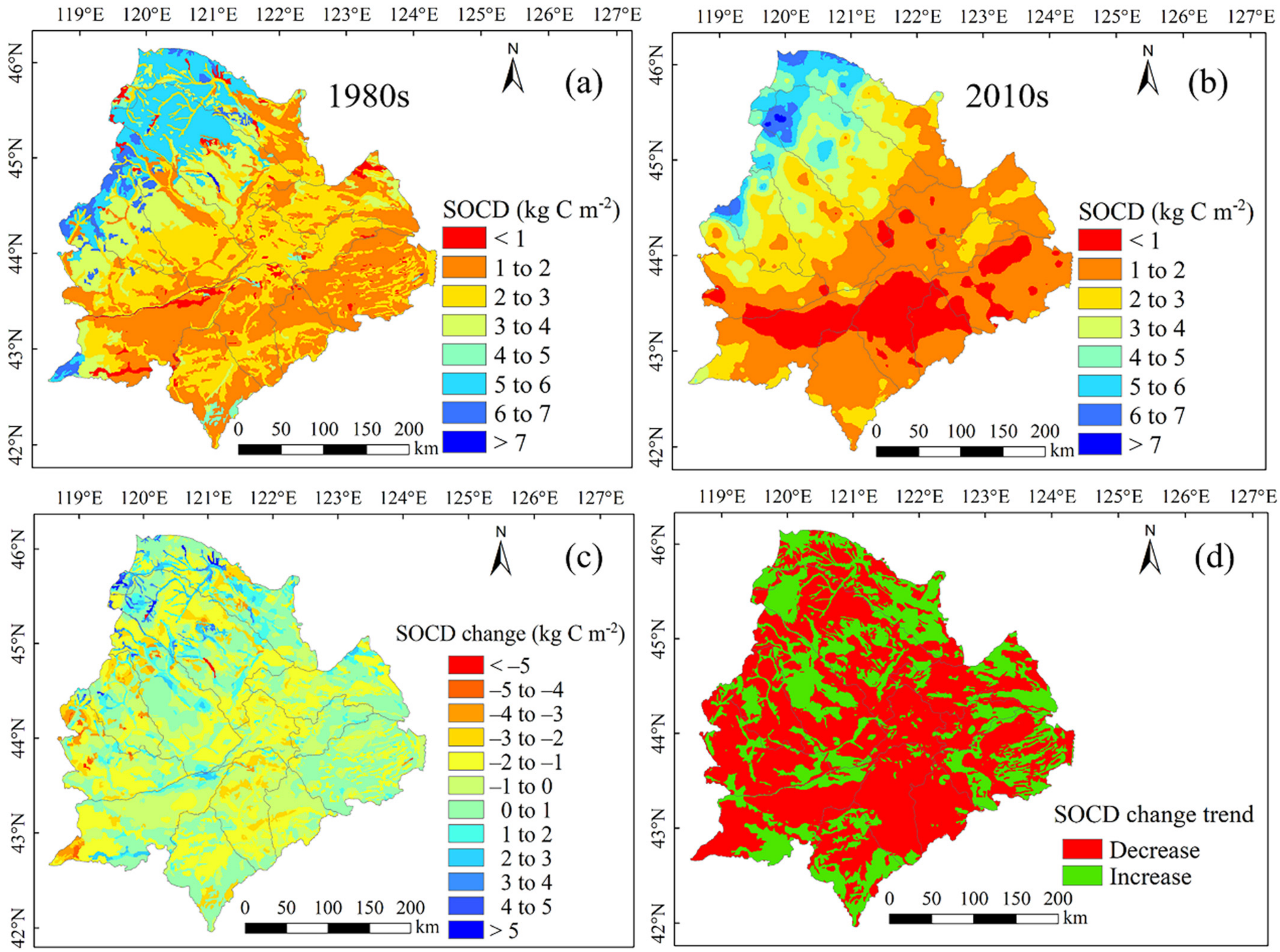

Fig. 5. Spatial distribution of the soil organic carbon density (*SOCD*) to a depth of 20 cm in (a) the 1980s and (b) the 2010s; (c) changes and (d) change trends for SOC from the 1980s to the 2010s.

ecosystems to cropland decreased SOC, a process that has been well recognized in the literature. The emission of CO_2 from the soil due to widespread desertification in arid and semiarid regions, which has been caused by a combination of climate change and unsustainable land use, also cannot be ignored as a contributor to increasing atmospheric CO_2 (Lal, 2001; Zhou et al., 2008).

The Mann-Kendall test indicated that from 1980 to 2015, our study area showed a significant increase in the mean annual air temperature ($Z = 2.74$, $P < 0.01$). Fig. 6a shows that most of the study area showed increasing temperatures, versus decreases only in the extreme south. In contrast, mean annual precipitation decreased, although the decrease was not significant ($Z = -1.40$, $P > 0.05$). Fig. 6b shows that the decrease was greatest in the northern and eastern parts of the study area. That is, the Horqin Grassland has undergone a warming and drying trend since 1980. We also performed stepwise regression and found that the region's decreasing SOC was significantly ($P < 0.001$) related to the combination of increasing temperature and decreasing precipitation, but the adjusted R^2 was small (0.042). This suggested that climate change can significantly explain the decrease in SOC storage, but was not the primary contributor to this decrease. Based on the dataset from the 2010s, correlation analysis indicated that *SOCD* was significantly positively correlated with NDVI (Pearson's $r = 0.269$, $P < 0.001$). This means that land cover change is a critical factor for the evolution of SOC.

The Horqin Grassland is one of the most seriously desertified regions of China. The current soils are dominated by Arenosols due to the severe desertification in the region, and these soils had the lowest *SOCD* (1.32 kg C m^{-2}), but accounted for 22.1% of total SOC storage (Fig. 4c and d). Our previous research in the study area (Li et al., 2006) found that along the spectrum from potential desertification to extremely severe desertification, SOC storage in grassland to a depth of 100 cm decreased by 90.0%. Apart from climate change, the increasing area of sandy land (here, only the extremely severely desertified land, with a vegetation cover < 5% and a soil surface covered by coarse sand) and cropland, combined with the decreasing area of grassland (Table 2), could explain the decrease in SOC storage in the Horqin Grassland during the study period. Many studies have supported this hypothesis. For example, Guo and Gifford (2002) found that land-use changes from native forest and pasture to cropland resulted in an average decrease of SOC storage by 42 and 59%, respectively. Yu et al. (2007a) found that desertification of grassland in northwestern China resulted in a 10.6% lower *SOCD* in grassland (8.24 kg C m^{-2}) than in cropland (9.22 kg C m^{-2}) across the country. Xie et al. (2007) also reported that China's grassland showed the highest net loss (3.564 Pg) in SOC storage over 20 years, primarily due to desertification during that period. A case study in southern Brazil (Bordonal et al., 2017) reported that SOC storage decreased by 44% after the conversion of pasture to cropland. On average, conversion of native grasslands to crop production results in an approximately 50% loss of SOC (Lal, 2018).

To restore the degraded ecosystems, restoration practices, mainly

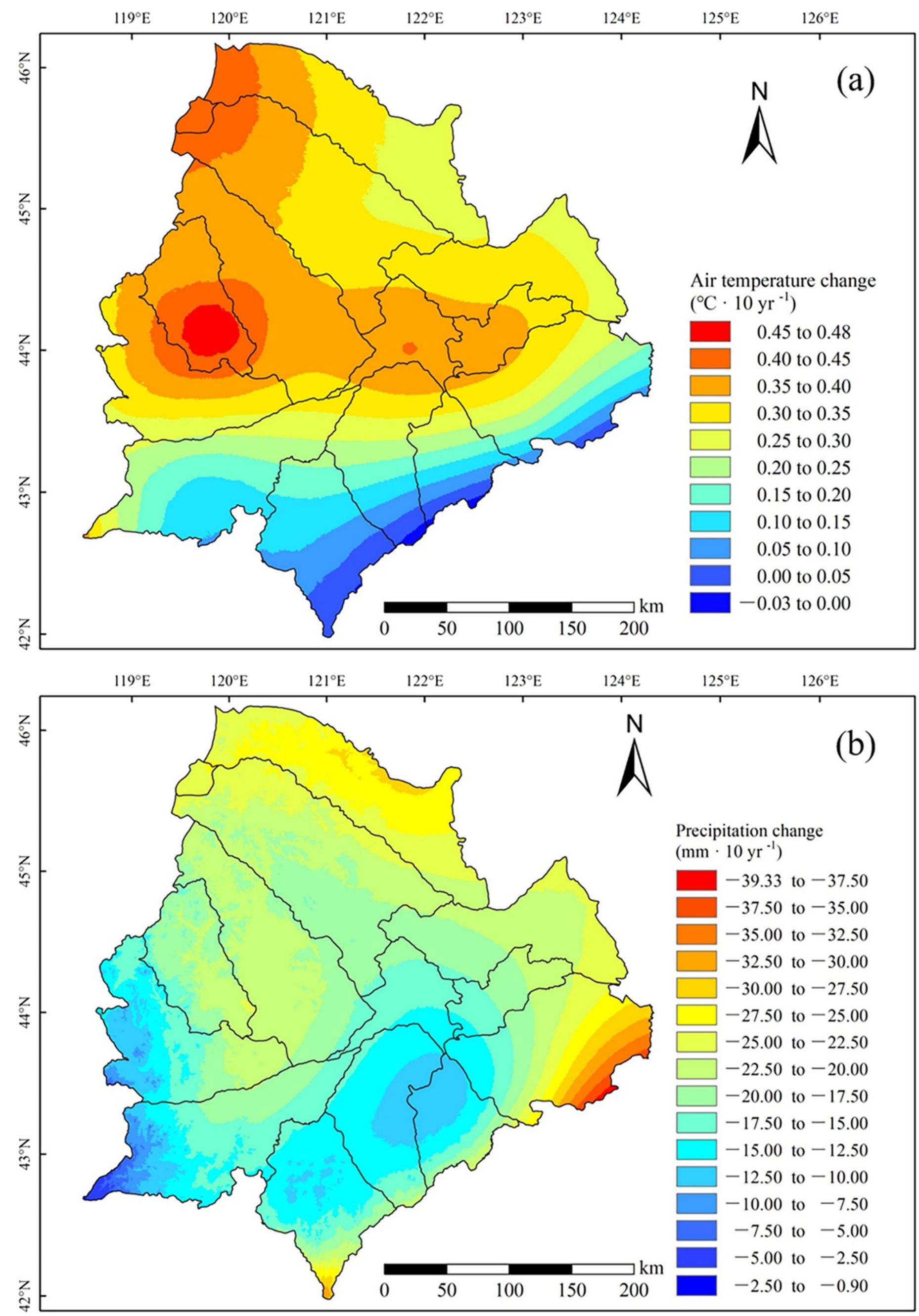

Fig. 6. Rates of change from 1980 to 2015 in (a) temperature and (b) precipitation per decade based on linear least-squares regression. Negative values represent a decrease since the 1980s.

including afforestation and grazing exclusion, have been gradually implemented in the Horqin Grassland since the late 1970s. These practices have previously been shown to significantly improve SOC storage in desertified areas. Previous studies of these techniques in areas with active dunes indicated that SOC storage to a depth of 100 cm increased by 56.6 g C m^{-2} yr^{-1} during a 25-year grazing exclusion (Li et al., 2012), versus 21.8 g C m^{-2} yr^{-1} during a 38-year afforestation period using Mongolian pine (*Pinus sylvestris* var. *mongolica*; Li et al., 2013), and 36.0 g C m^{-2} yr^{-1} during a 31-year afforestation period using *Caragana microphylla*, a perennial leguminous shrub (Li et al., 2017). The Horqin Grassland is one of the key areas for implementation of China's first national key restoration project, the “Three-Norths Shelter Forest Program”. Under this program, the woodland area increased by 53.6%, leading to an increase of 14.72 Tg C in SOC storage during the study period (Table 2). The effectiveness of the restoration practices could explain why some sites in Fig. 5c and d showed increased SOC storage. However, the increase in SOC storage due to expansion of the woodland area could not compensate for the overall decrease caused by shrinkage of the grassland area. The estimates of SOC storage for the whole study area therefore decreased during the study period.

According to an assessment of the dynamics of desertification in the Horqin Grassland (Duan et al., 2014), the total area of desertified land increased rapidly between 1975 and 1990 under the combined effects of climate change and improper human activities, and then decreased gradually between 1990 and 2010 due to the implementation of a series of ecological restoration practices. This suggested that the region's environmental conditions have been improving since the 1990s, and researchers therefore assumed that SOC storage would show an increasing trend. However, our results show the opposite trend for SOC

storage. We hypothesize the following reasons for this contradiction:

1. During the observation period from 1975 to 2010, the total area of desertified land reached its peak in 1990, but from 1990 to 2000, both severely and extremely severely desertified land expanded obviously (by 14.3 and 30.6%, respectively), despite a decrease in the total area of all classes of desertified land. In particular, some slightly desertified land changed to severely and extremely severely desertified land. This conversion was accompanied by great carbon loss (by 72.8 and 79.3%, respectively) from the soils (Li et al., 2006). This means that the worst SOC situation in the study area occurred in the 1990s. It is possible that we would observe an increasing trend in SOC storage if we used the SOC level in the 1990s as the baseline to quantify the changes.
2. The process of restoration of degraded soils is very slow. In our previous research, we estimated that it would take 117 to 205 years to fully restore the SOC storage (to a depth of 100 cm) of the extremely severely desertified land in the Horqin Grassland through afforestation (Li et al., 2017). Therefore, a given desertified area may appear to be reversing the degradation based on its improving vegetation cover due to restoration practices, but this does not necessarily mean that its SOC level will show substantial improvements over a short period. Fig. 2k and l illustrate how the surface soil may remain mobile and impoverished as a result of overgrazing, even after decades of afforestation.

In the present study, we derived the spatial patterns of *SOCD* for both the 1980s and the 2010s from spatial interpolation to allow a comparison between the two periods. Although there is inevitably some uncertainty due to interpolation in a region with high heterogeneity, our large sample size and dense coverage of the majority of the study area would reduce this uncertainty. The lack of soil bulk density data introduces some additional uncertainty in our estimates of SOC storage during the 1980s, which in turn will introduce uncertainty in estimates of the storage changes. However, when bulk density data is unavailable, it is common to estimate bulk density by creating a reliable relationship between bulk density and the SOC concentration (Bellamy et al., 2005; Post and Kwon, 2000; Xie et al., 2007; Yang et al., 2009). Our results (Fig. 3) suggest that our derived relationship was reliable.

Another source of error is that the soil sampling locations used during the 1980s were not the same as those we used during the 2010s, and given the high spatial variation in SOC, that would also be an error source for our estimates. The large sample size used in the present study should minimize this error. The application of the Walkley-Black dichromate oxidation procedure to determine the SOC concentration may also create uncertainty if the values are compared with the results obtained using other methods (e.g., using a CN analyzer). However, we chose the same method that was used to analyze the 1980s samples to avoid the uncertainty that might arise from using different methods. In future research, it may be worthwhile to calculate a conversion factor between the values obtained using the Walkley-Black method and more accurate methods for our soils. Although there is considerable uncertainty due to the abovementioned sources, we found (*t*-tests, $P < 0.001$) that the *SOCD* values in the 2010s were significantly lower than the *SOCD* values in the 1980s for the study area as a whole. This confirms that the overall decreasing trend is significant.

Another problem with the present estimates is that we did not include the carbon stored in vegetation at the sampling sites in the present study. It is possible that even though SOC storage decreased, total carbon sequestration at a site (soil + vegetation) may have improved. In future research, it will be necessary to comprehensively study all of the carbon stored in the plant–soil system, and to obtain more data on the relative weights of the factors that influence the dynamics of carbon storage in the ecosystems of the Horqin Grassland.

5. Conclusions

China's ecologically fragile Horqin Grassland showed a large decrease in SOC storage from the 1980s to the 2010s based on a comparison of data collected from 2011 to 2017 (the 2010s) with data collected from 1980 to 1987 (the 1980s). Climate change (increasing temperatures and decreasing precipitation) appears to have combined with land-use and cover type changes (particularly the conversion of grassland to cropland) and the expansion of desertification to reduce SOC storage. The present study represents the largest field inventory that has ever been conducted in this region, with the highest density of soil sampling and the most accurate estimates of SOC storage. The SOC levels in the 2010s provide an important updated baseline for evaluating changes in SOC storage and its response to variations of environmental resources and human activities. Our estimates of SOC storage, its trends over time, and its spatial distribution will help policy makers achieve develop policies to achieve sustainable development of agriculture, forestry, and animal husbandry in the study area based on improved carbon sequestration.

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